The role of soil aggregates in the recovery of soil C and N in a restored tallgrass prairie chronosequence

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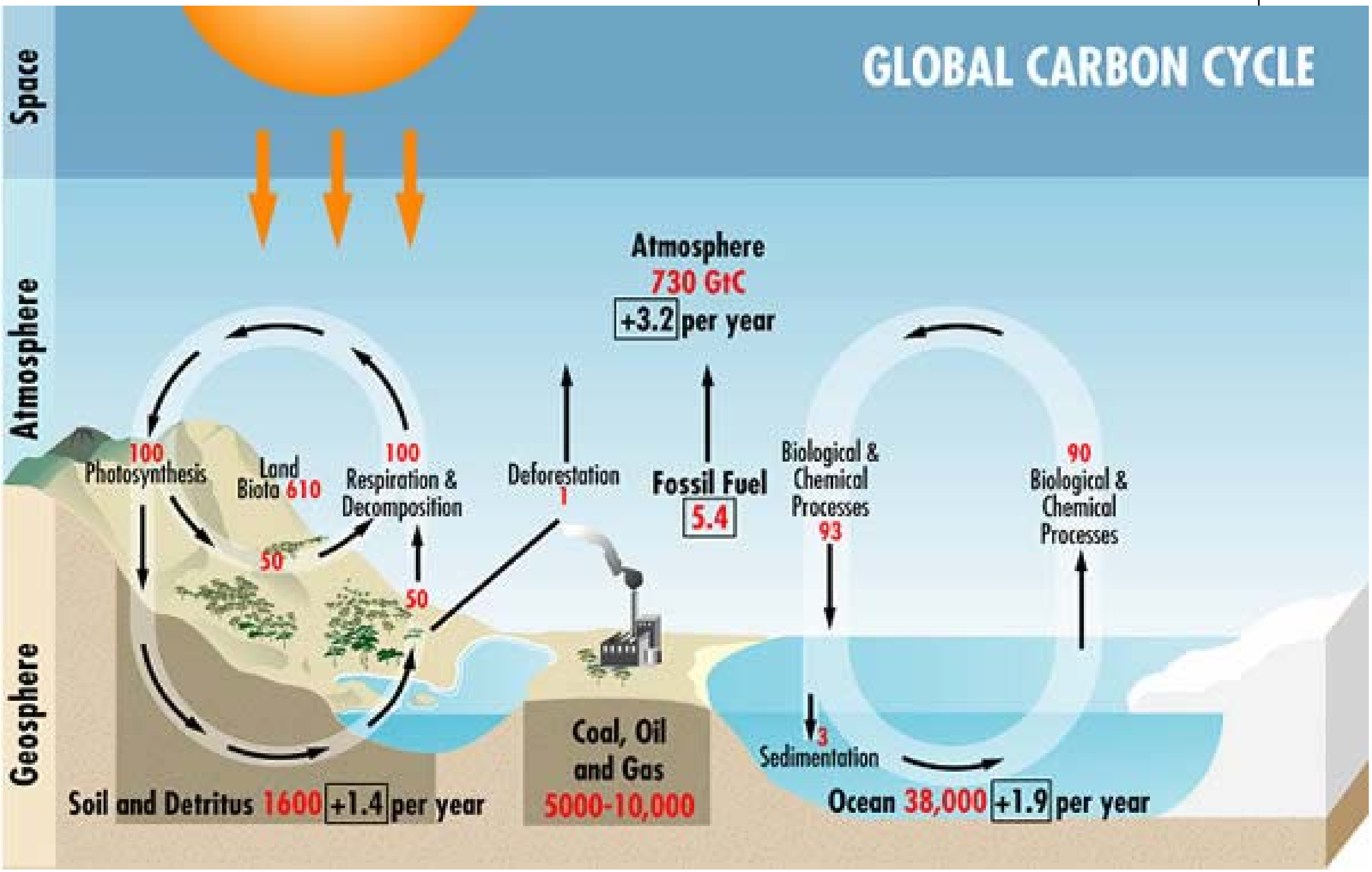
Terrestrial carbon sequestration

- Atmospheric CO_2 is rising
- Cutting emissions is … difficult
- Ecosystems may help by transferring atmospheric CO_2 to biomass and soil
- Why soil?

Soil: large, stable C pool

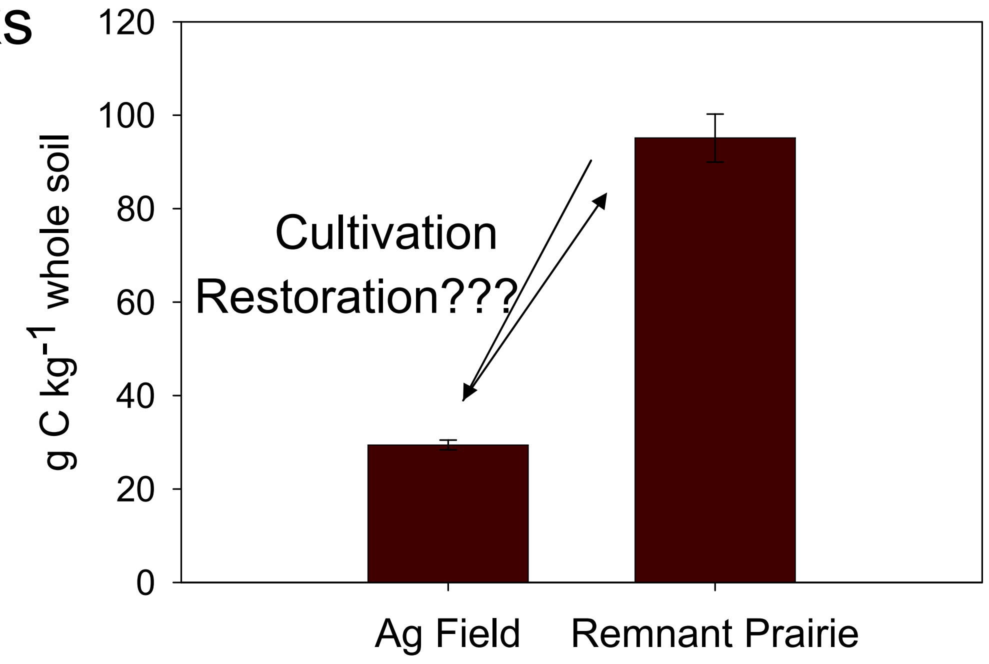


Soil – Our single most valuable ecosystem

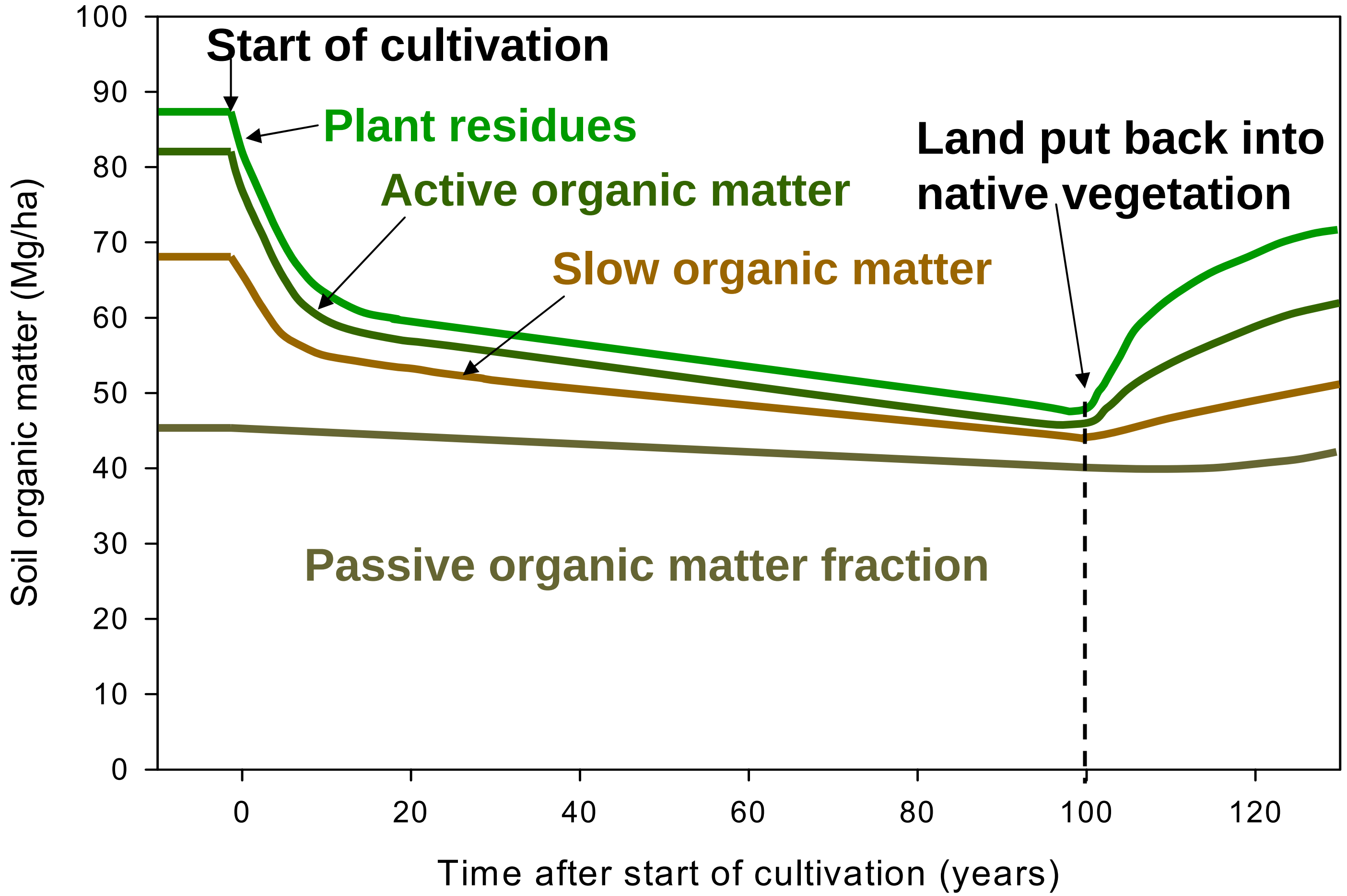
- Extremely diverse *living* ecosystem
- Ecosystem services
  - soil (OM cycling)
  - clean water
  - food etc.
  - genetic resources

Terrestrial carbon sequestration: soil can be a C sink

- Land use (agriculture, deforestation, urbanization) has depleted soil C stocks
- Potential for soils, especially in temperate perennial grasslands, to provide C sink
- Need better understanding of controls on soil C dynamics



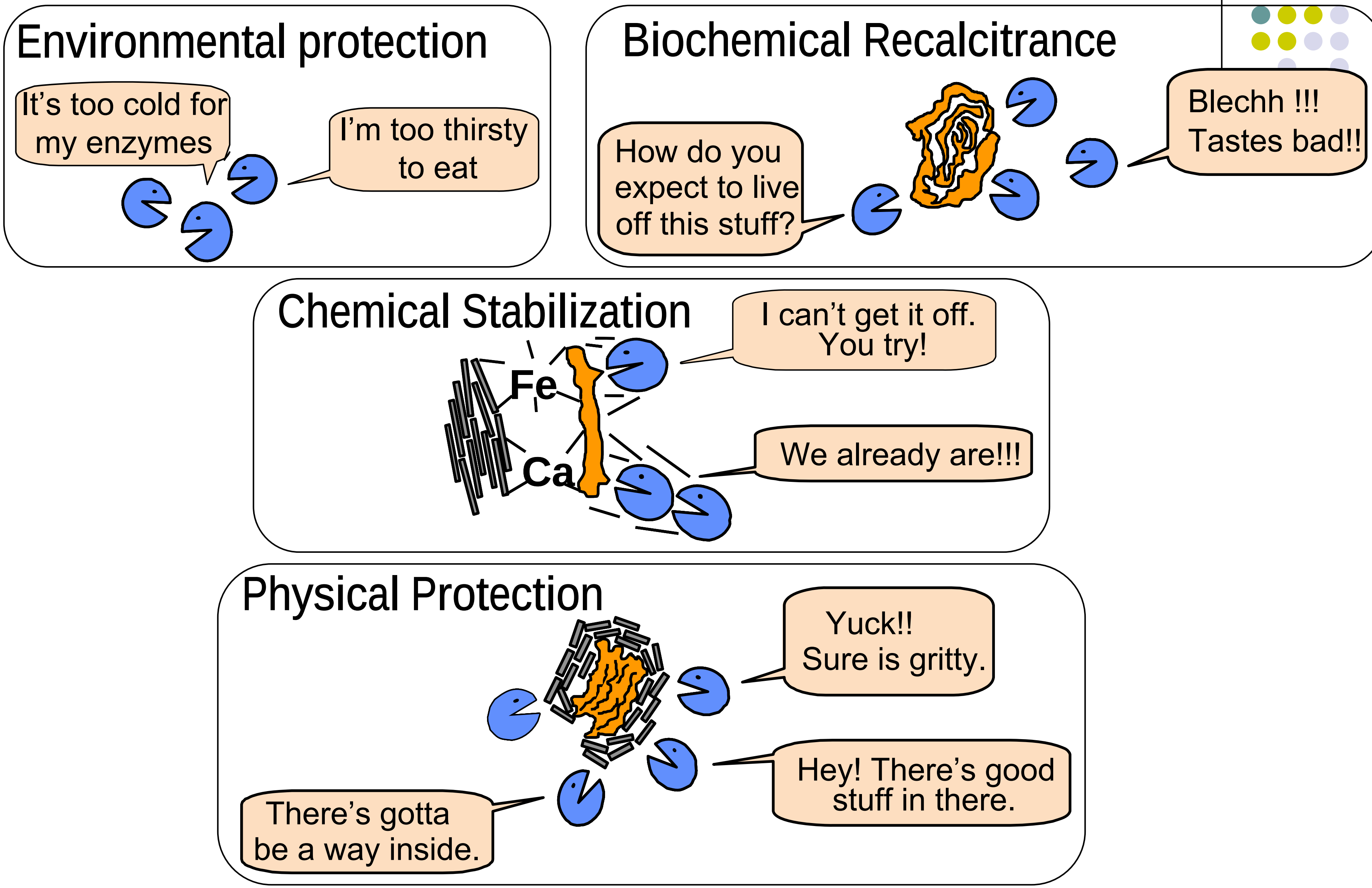
SOM pools: loss after cultivation, gain after restoration



From Brady and Weil 1999

Mechanisms of soil organic matter stabilization

From Jastrow and Miller (1998) *In* Soil Processes and the Carbon Cycle, CRC Press



Soil structure

- Exists in three dimensions
- Dynamic and heterogeneous in space and time
- Habitat of all soil biota
- Framework in which and through ALL soil processes occur
- Provides physical protection

Soil structure – an integrator of many soil processes

Root growth & turnover
Food web dynamics
Decomposition
Physicochemical protection
of organic matter
Humification

Erosion
Runoff
Infiltration
Hydraulic conductance
Gaseous diffusion
Aeration

Mineral weathering
Ion exchange
Leaching
Solute transport
Nutrient cycling
Carbon cycling

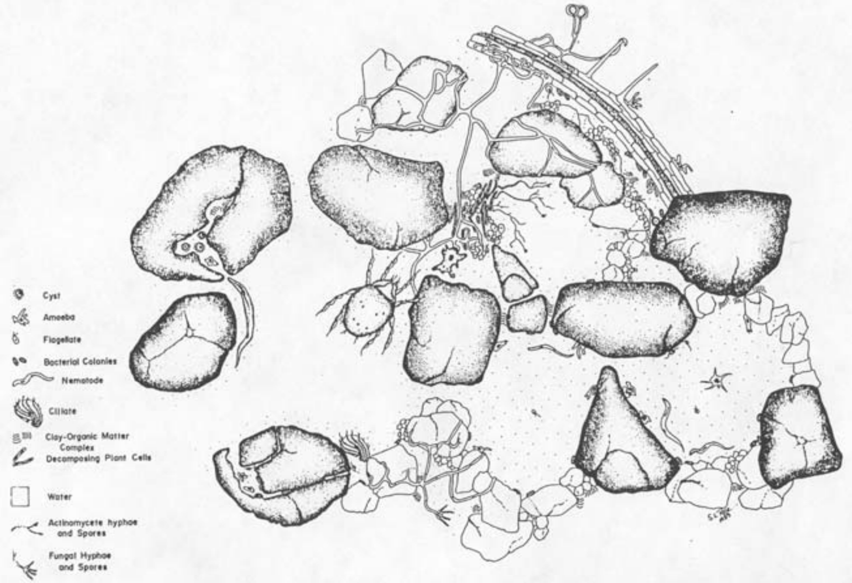
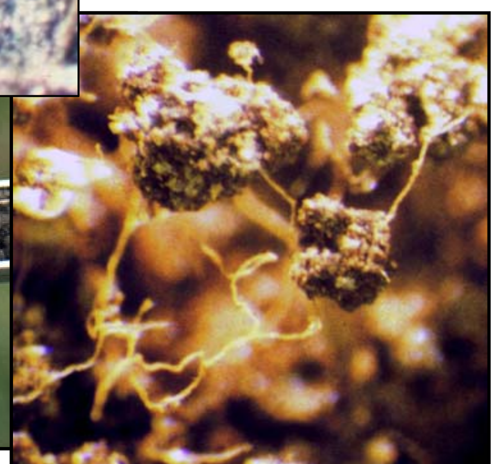


Fig. 4. Horizontal cross section (1 cm^2) of a highly structured and biologically active microsite in the short grass prairie. It depicts how the different classes of pore space and the distribution of water within pores influence the feeding and habitat relationships among the different groups of soil organisms. Illustration by S. L. Rose.

Soil aggregation

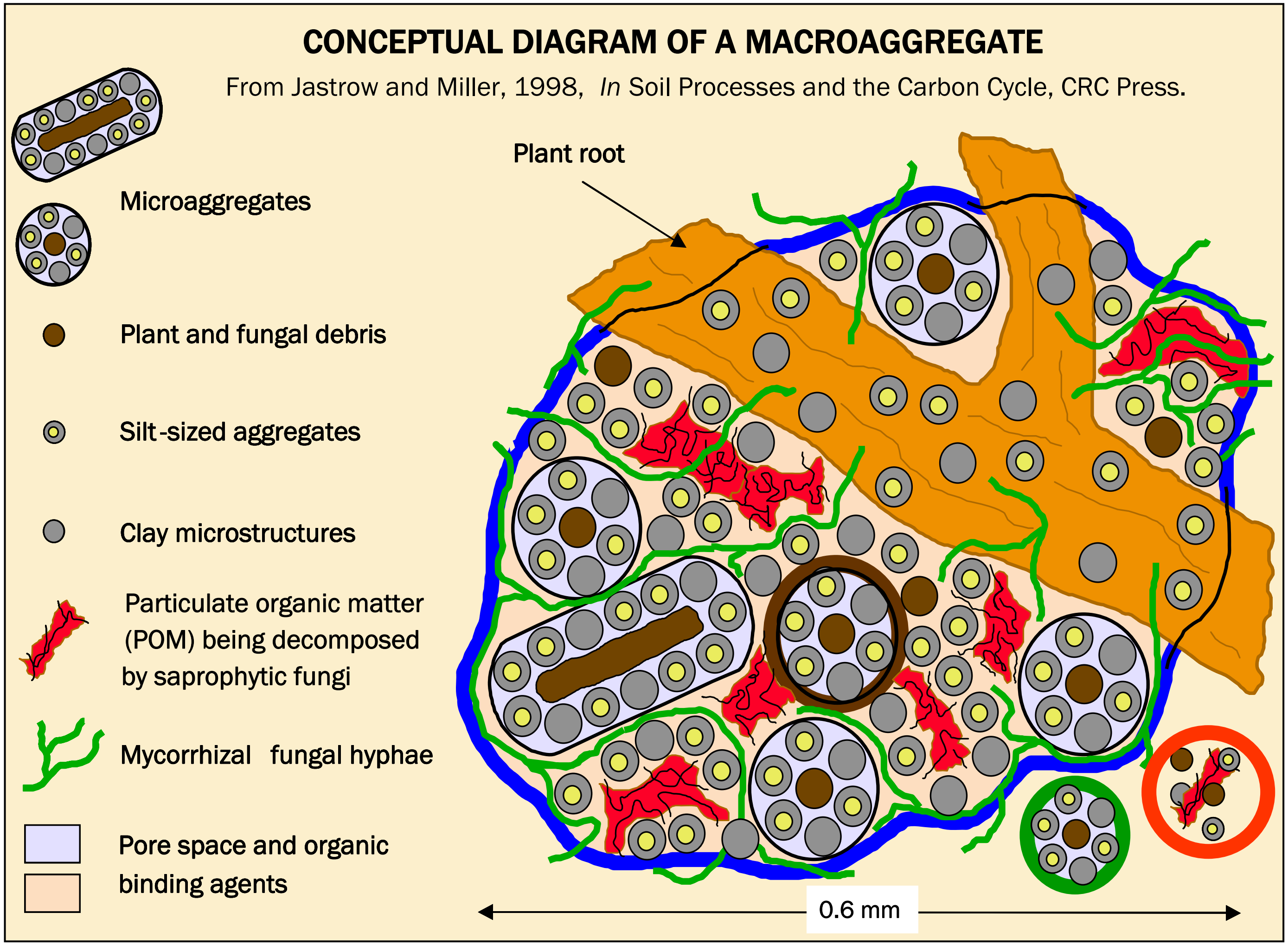
"... the naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates."

J. P. Martin et al. 1955. Soil aggregation. Advan. in Agronomy 7:1-37.



Highly structured soils have a diversity of pore sizes created by the hierarchical organization of soil aggregates

Aggregate hierarchy



Can soil be restored?
Can soil sequester CO_2?

Bellmuseum.org

?

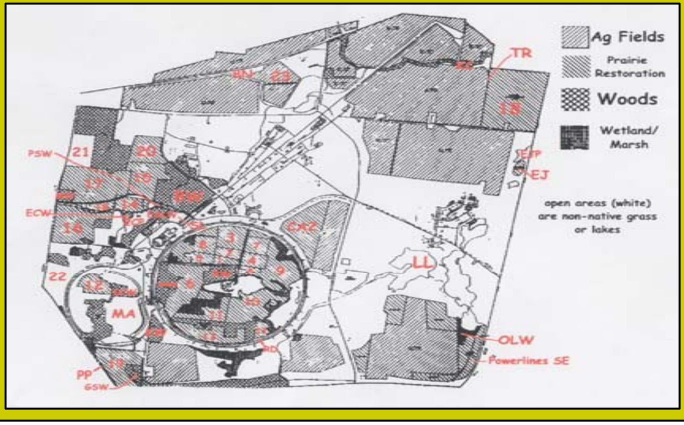
- After planting native prairie plants, does the soil return to precultivation conditions?
- Will the ecosystem function as though it had never been disturbed?
- Will SOM return?

What controls soil C dynamics in restored prairie?

- C sequestration
  - How much C will restored prairies accumulate?
  - How fast will it build up?
  - How long will it remain in the system?
- Provide data for models
  - Real-world data to parameterize soil C models
  - Thorough understanding of this system may help us know what to expect from others

Study site: Fermilab restored prairies

- Restoration of native tallgrass prairie began 1975
- Annual plantings create a chronosequence of restorations encompassing over 400 hectares.



Fermilab restored prairies : aboveground

First year

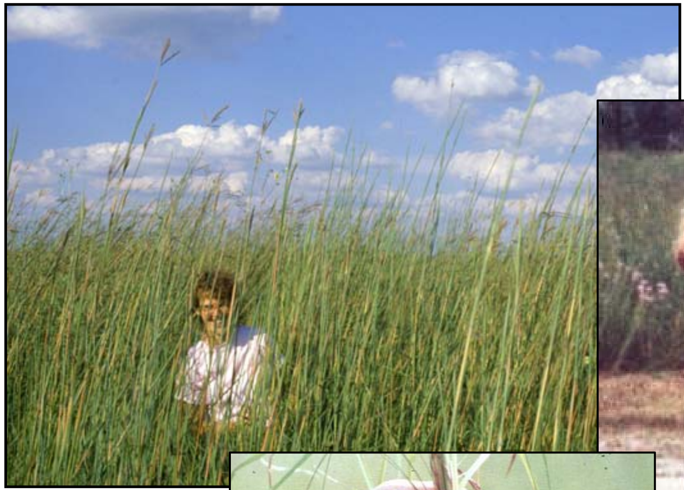
Second year

Eleventh year

- Initial years are dominated by species typical of old-field succession (annuals → biennials → weedy perennials).
- Once litter buildup is sufficient to carry a fire, prairie grasses and forbs begin to take over.

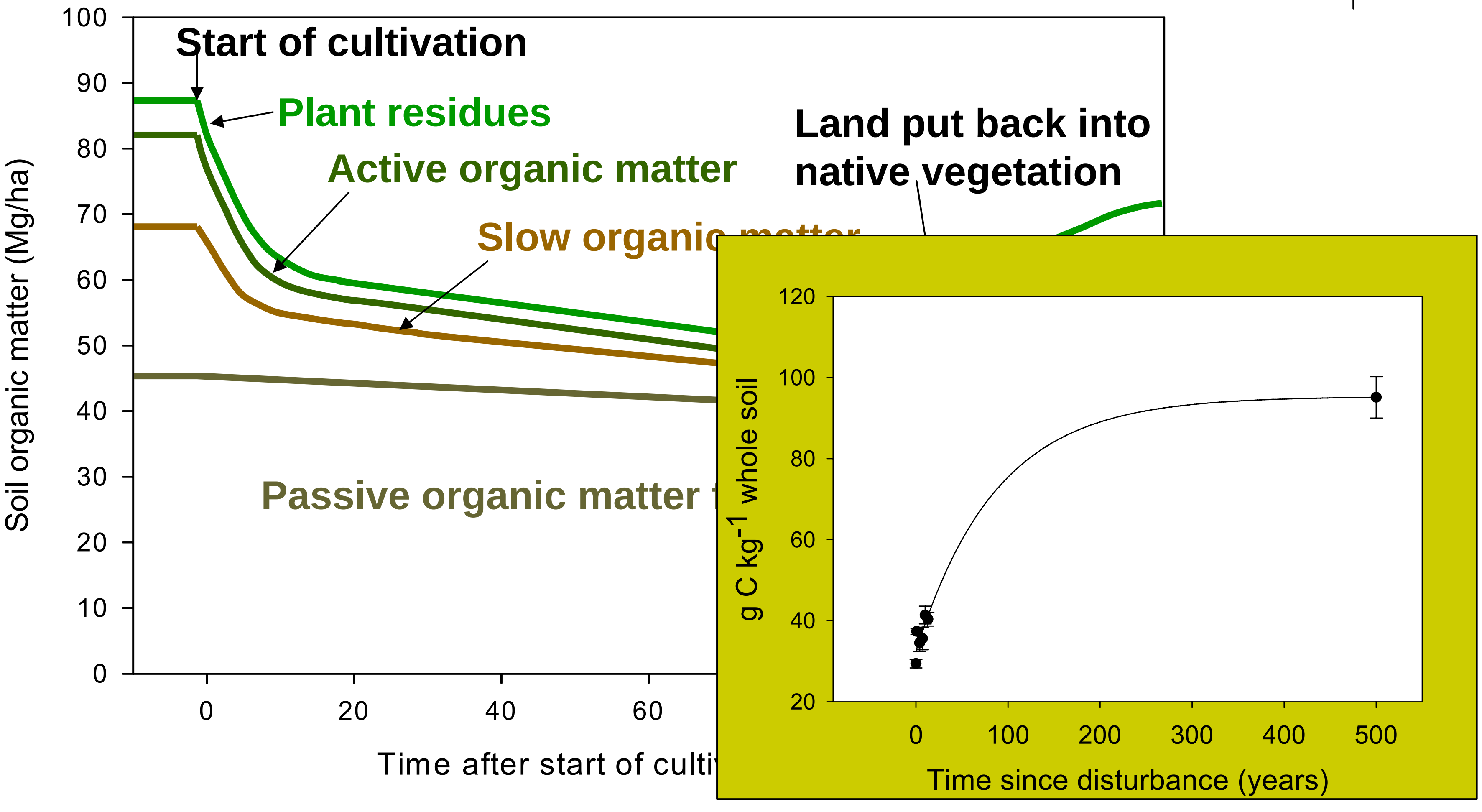
Fermilab restored prairies: belowground

- Highly structured silt loams degraded by a century of agriculture.



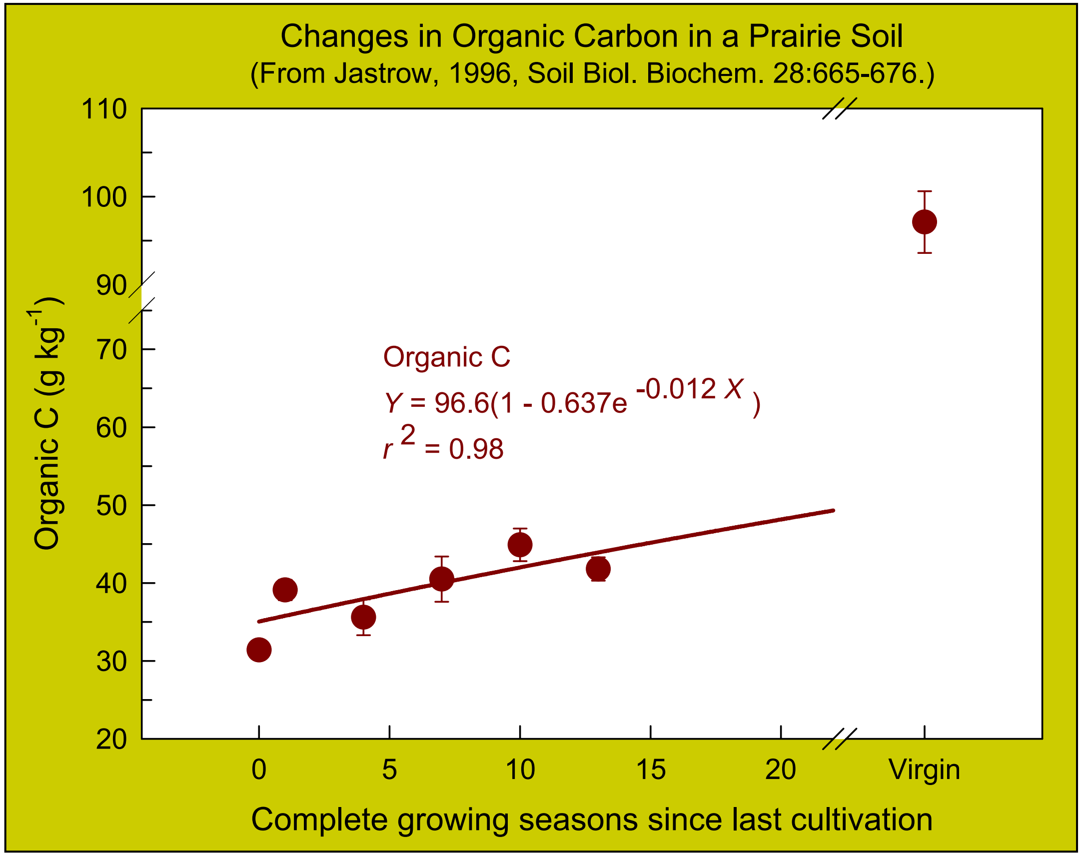
- Peak standing crops can be over 1 kg dry wt m^{-2} aboveground and 2 kg dry m^{-2} belowground.
- Surface litter is burned regularly → belowground inputs drive soil system

Fermilab prairies have accumulated SOM



Jastrow 1996

SOC takes much longer to recover



- Soil organic C takes ~ 380 years to return to precultivation levels.
  - Why?
  - How?
  - Organic matter goes into the soil, but what happens to it?

Physical protection and SOM accrual

- Rate of SOM accrual not expected to remain linear
- Controls on longevity of SOM not fully explored
- Capacity of soil to protect SOM may be limited

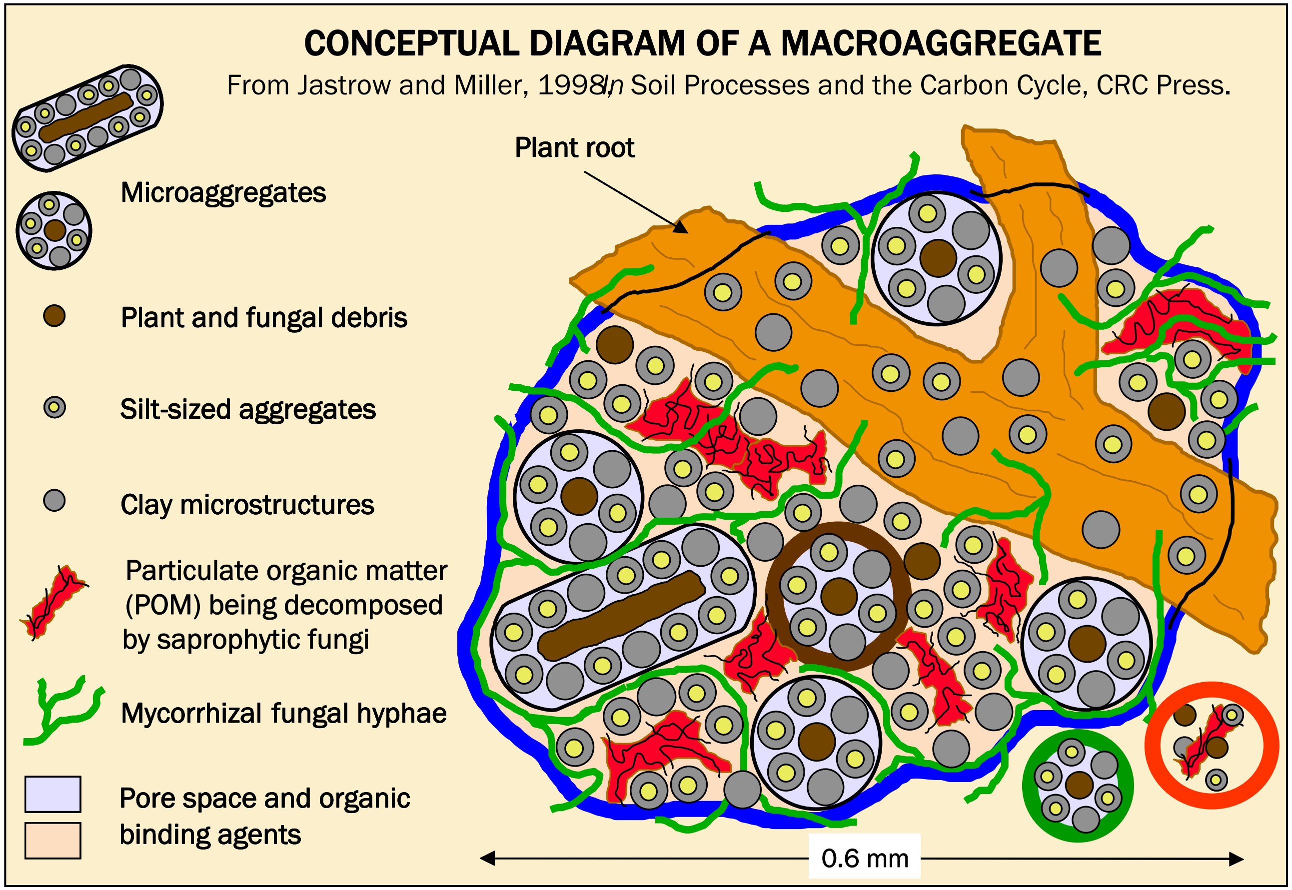
- Objectives
  - Investigate how hierarchical soil aggregates determine SOM accrual
  - Determine if some pools reach steady state faster than others → protective mechanisms may have saturated

Chronosequence approach

- Agricultural field
  - Soybean phase of corn/soybean rotation
  - Time zero
- Restored prairies
  - 3, 8, 16, 18, 21, 23 completed growing seasons
- Remnant prairie
  - Equilibrium or steady state condition
  - Constrains model

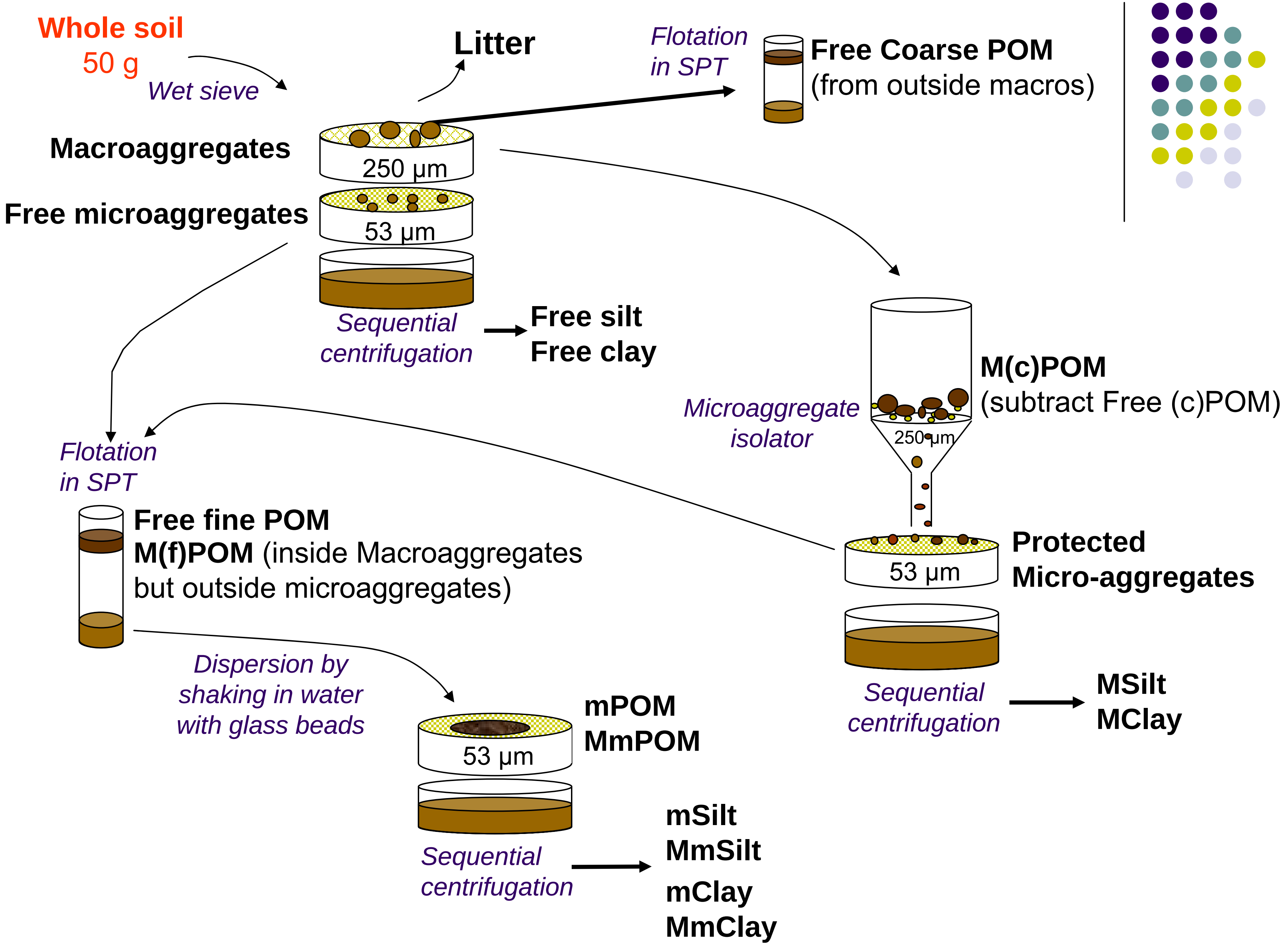
- $C_t = C_o + C_a (1-e^{-k*time})$ where
  - C_o is the initial C content estimated from the agricultural field,
  - C_a is the accrued C,
  - $C_o + C_a$ is the equilibrium C content estimated from remnant prairie,
  - C_t is C content at time *t*,
  - k is the first-order rate constant for loss of C; MRT is -1/k.

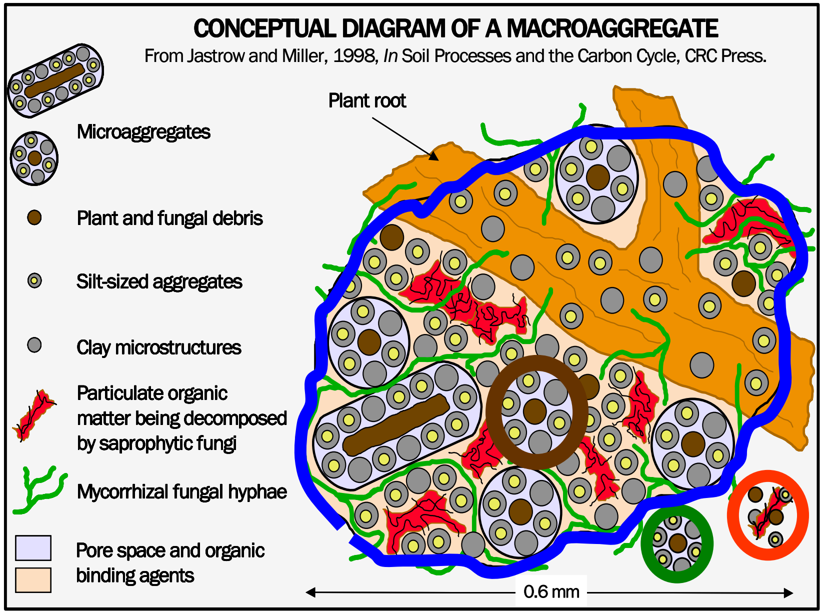
  - 500 years was the assumed age for remnant prairie because the time to 99% of equilibrium is accommodated by this age.



We expect

- The best protected soil organic matter pools to reach steady state ("saturate") first.
- Unprotected pools will only reach steady state as a result of equilibrium between plant inputs and decomposition, primarily controlled by climatic conditions (Stewart et al., 2007, 2008).

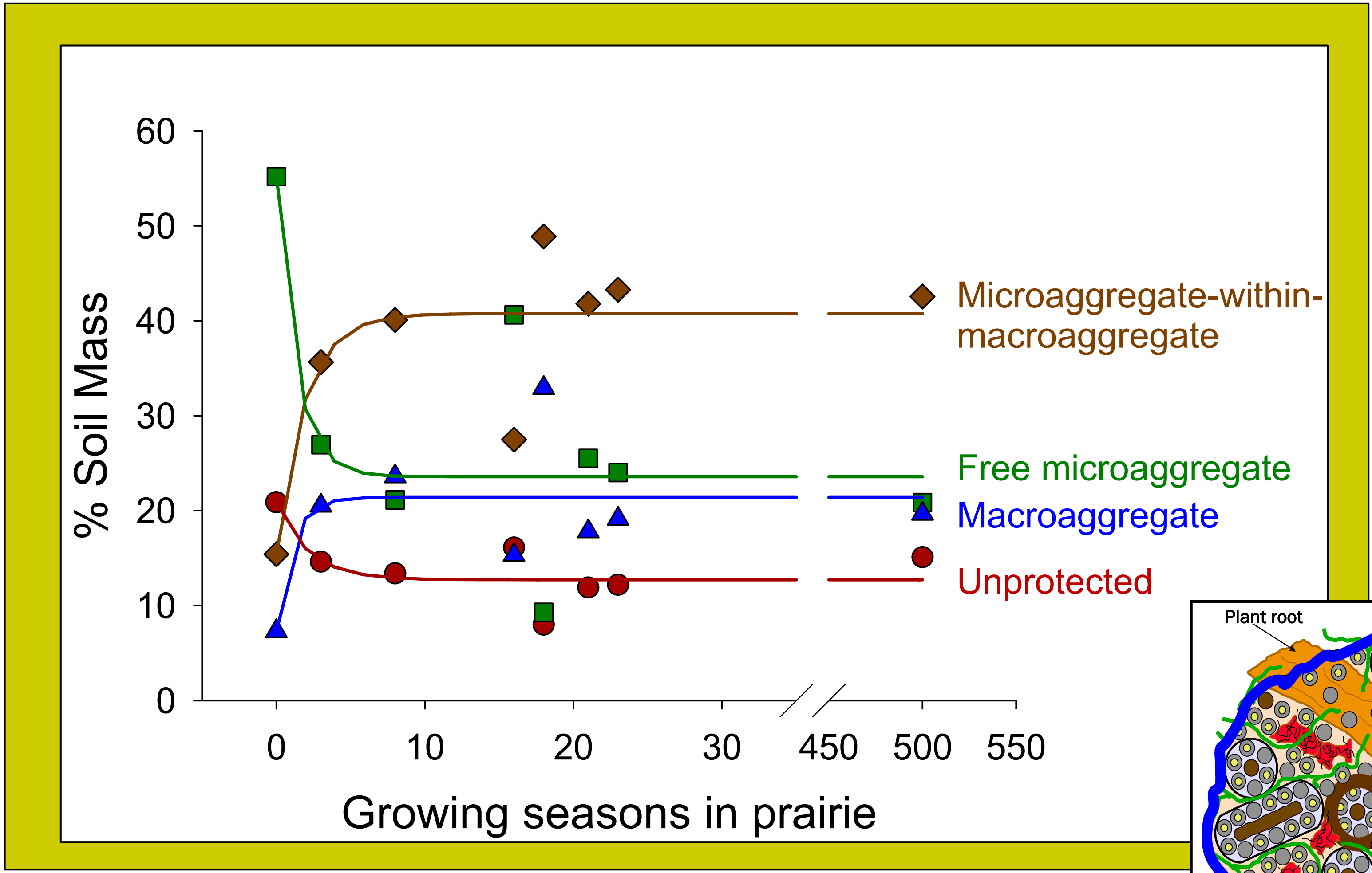

Whole soil
50 g
Wet sieve
Litter
Flotation
in SPT
Free Coarse POM
(from outside macros)
Macroaggregates
250 µm
Free microaggregates
53 µm
Sequential
centrifugation
Free silt
Free clay
M(c)POM
(subtract Free (c)POM)
Microaggregate
isolator
250 µm
Flotation
in SPT
Free fine POM
M(f)POM (inside Macroaggregates
but outside microaggregates)
Protected
Micro-aggregates
53 µm
Sequential
centrifugation
MSilt
MClay
Dispersion by
shaking in water
with glass beads
53 µm
mPOM
MmPOM
Sequential
centrifugation
mSilt
MmSilt
mClay
MmClay

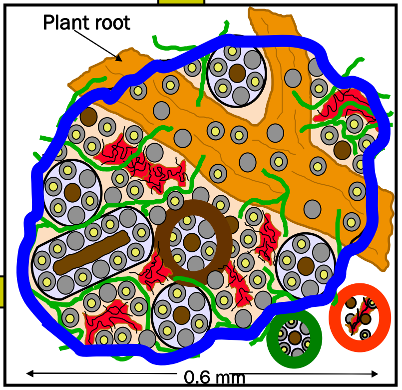


Fractionation yields POM, Silt, and Clay for each of level of aggregate protection.

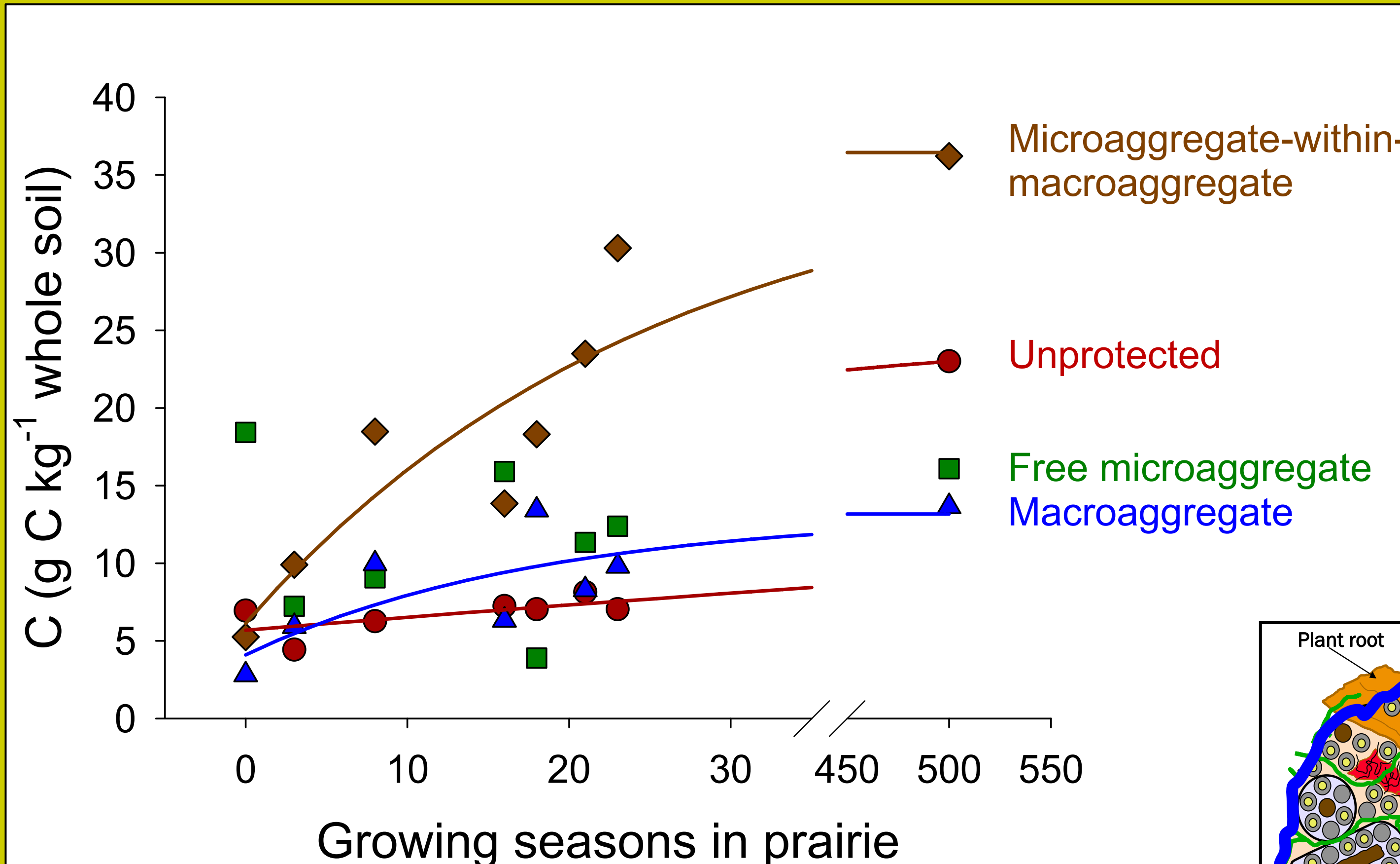
Unprotected	Macroaggregate	Free microaggregate	Microaggregate-within-macroaggregate
POM *Litter + F cPOM + F fPOM*	**POM** *>250 – F cPOM + M(f)POM*	**POM** *mPOM*	**POM** *MmPOM*
Free Silt	**MSilt**	**mSILT**	**MmSILT**
Free Clay	**MClay**	**mCLAY**	**MmCLAY**

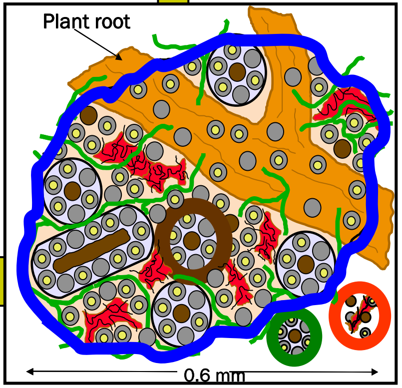
Soil structure recovers quickly





Aggregate-protected SOM takes longer to recover





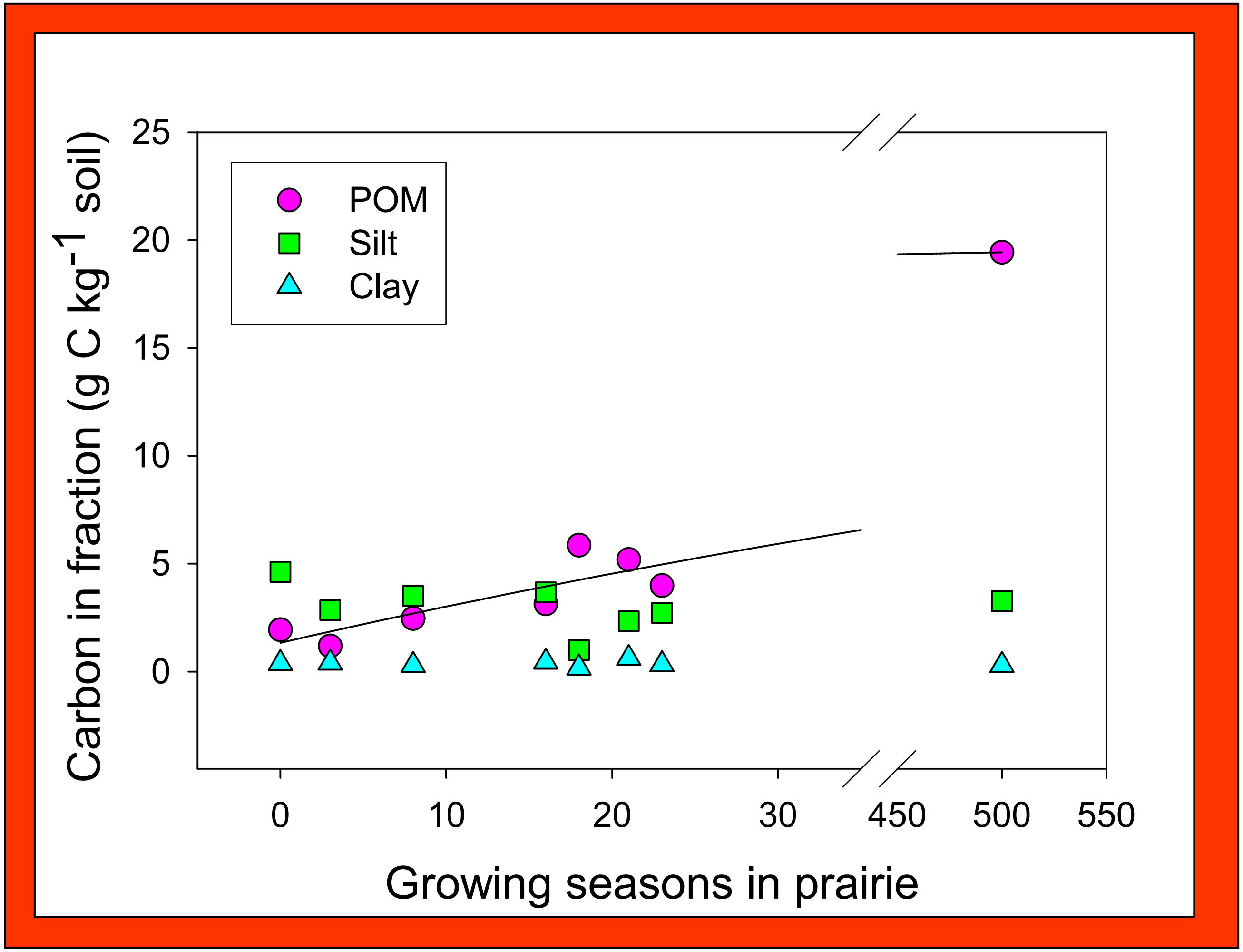
Time to accrue 95% of steady-state (years)

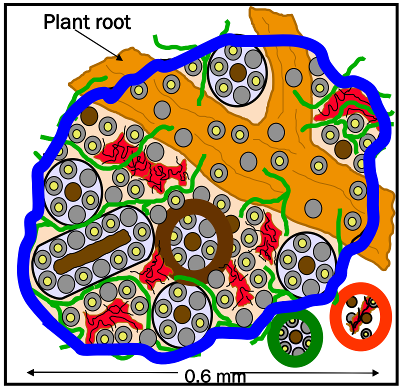
	Unprotected		Macro-aggregates		Free micro-aggregates		Microaggregate-within-macroaggregates	
	0-5	**5-15**	**0-5**	**5-15**	**0-5**	**5-15**	**0-5**	**5-15**
Mass	6.5	4.0	3.2	NA*	3.9	NA	5.6	NA
MRT	2.2	1.3	1.0	NA	1.3	NA	1.9	NA
Carbon	>500	>500	54.5	NA	NA	97.9	75.8	174.2
MRT	~200	~300	18.2	NA	NA	32.7	25.3	58.1

- SOM builds up in aggregates even after the structure is formed
- Pore spaces filling over time

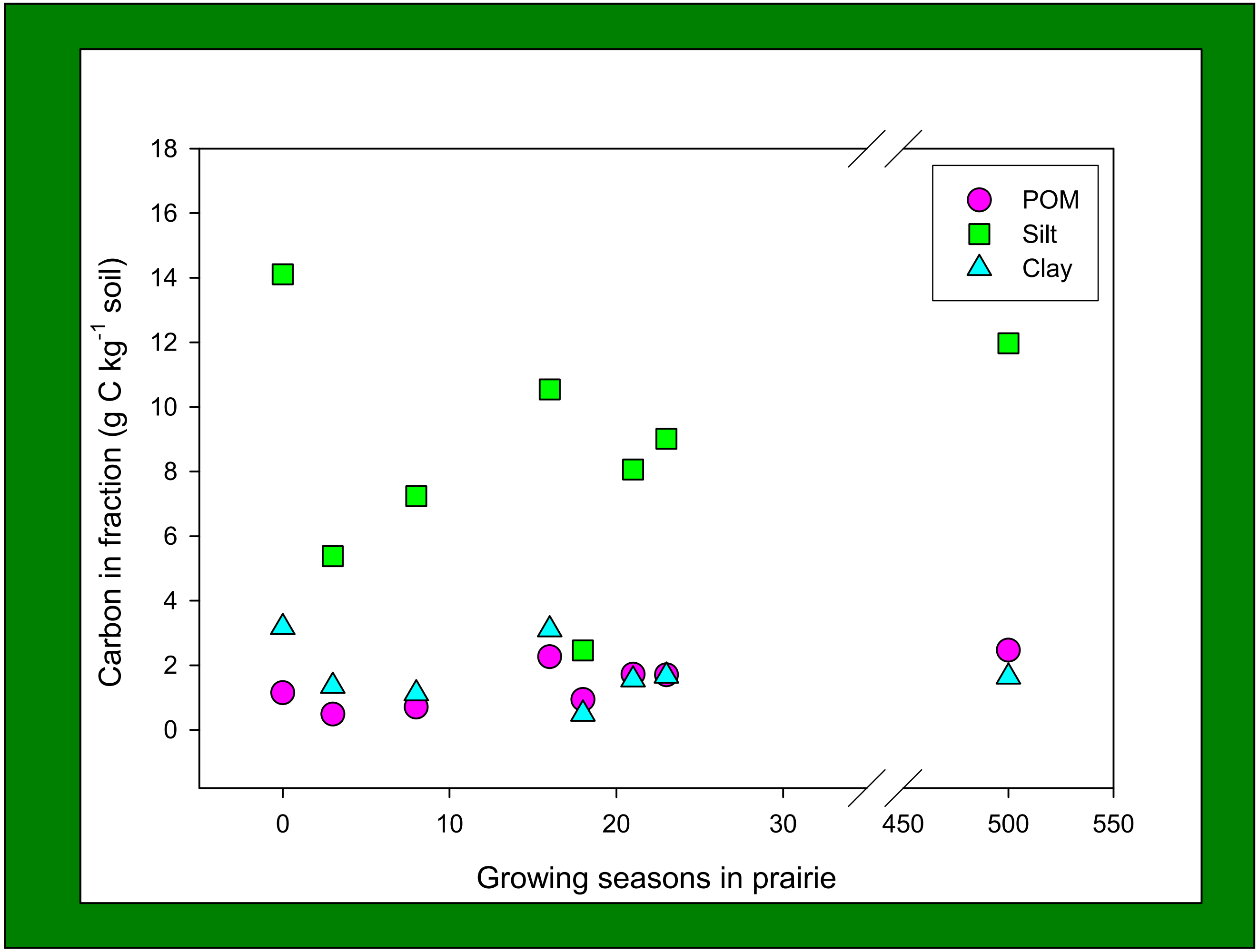
* Data did not fit model

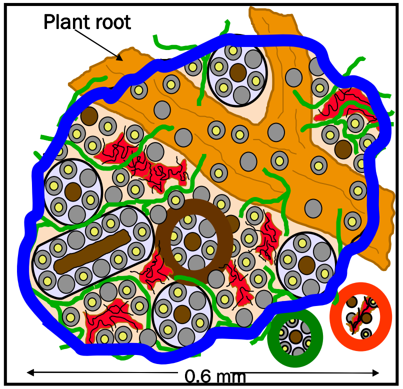
Unprotected pools



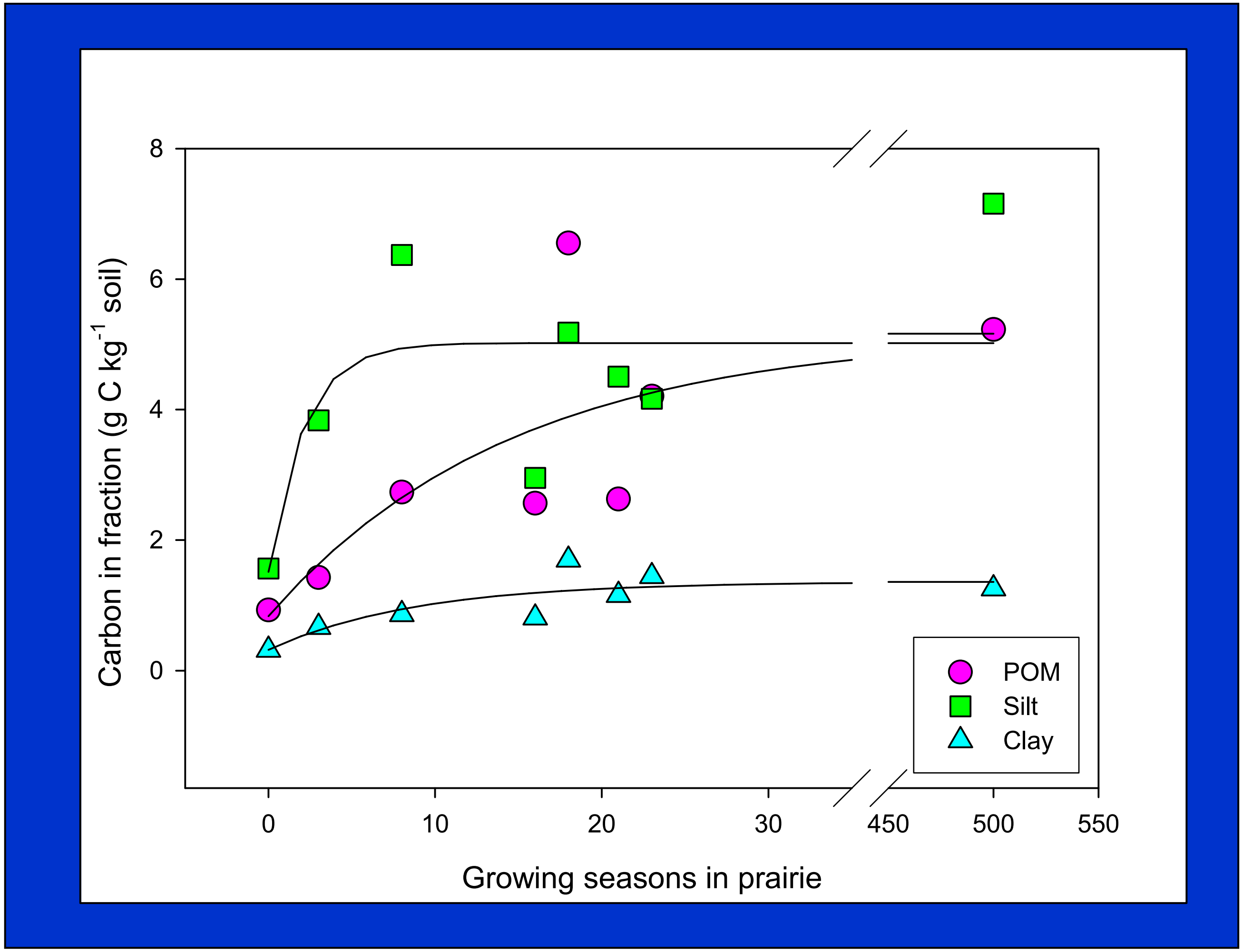


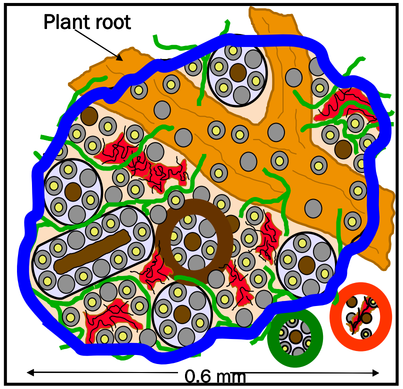
Free microaggregates



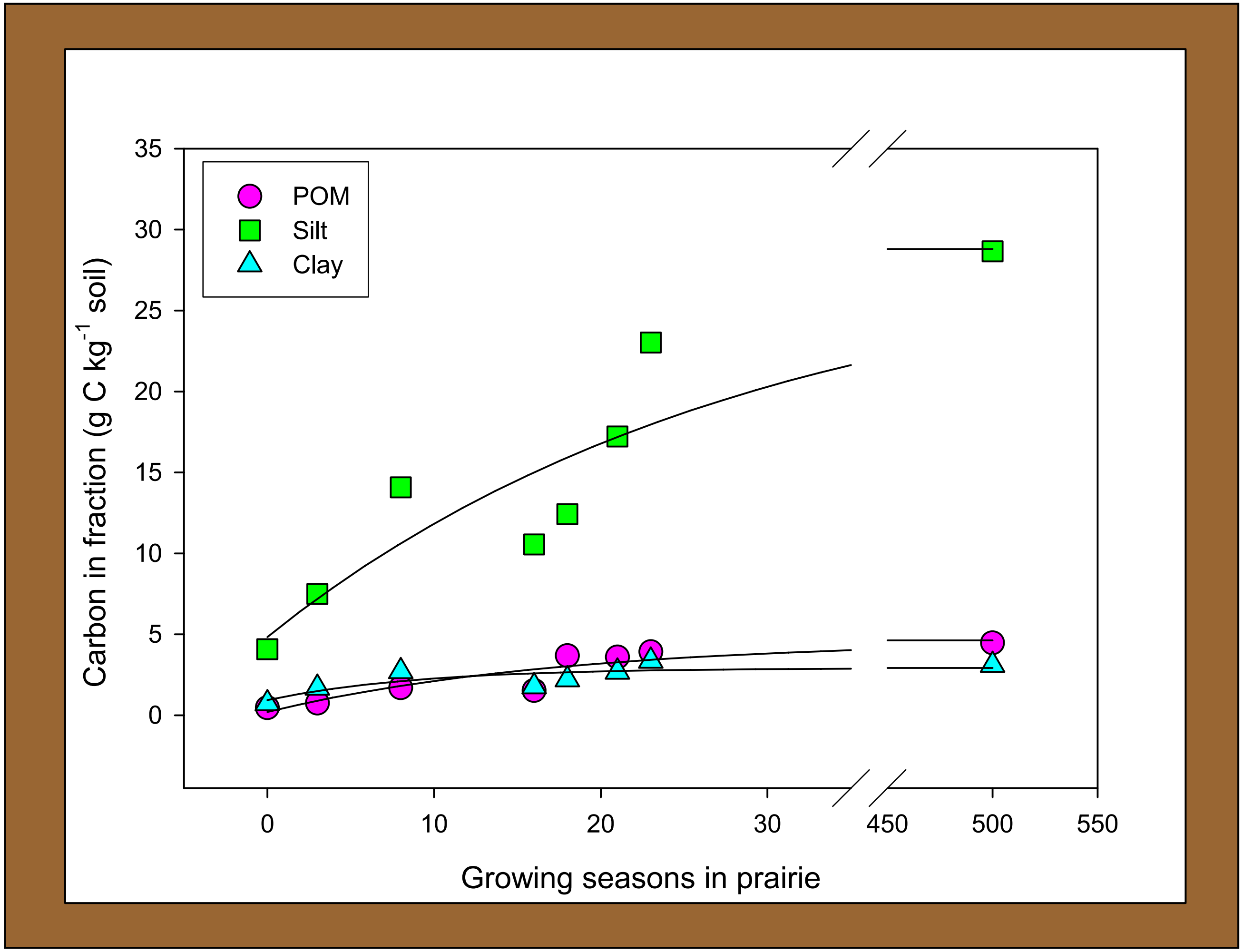


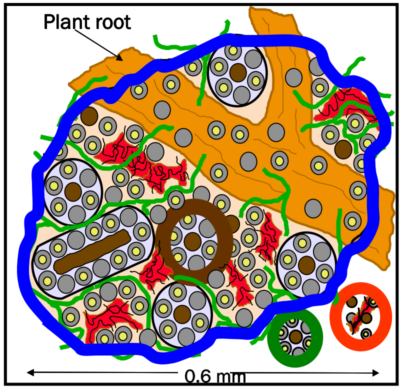
Macroaggregates





Micro-within-macroaggregates





Summary

- Some fractions are too variable to model – replicates may help
- C accumulates in aggregates even after the structures are formed.
- Some pools reach steady state before others → protection is saturated
  - Little or no accumulation in clay
  - Accrual is slowest in unprotected pools and is attributable to the Unprotected POM

Conclusions and implications

- Soil fractions behaved as expected, with unprotected pools approaching steady state only after protective capacity filled (Kool et al., 2007; Stewart et al., 2007; West and Six, 2007; Stewart et al., 2008).
- Potential for saturation.
  - Mineral pools reach steady state before unprotected pools, especially unprotected POM.
  - Unprotected SOM vulnerable to environmental changes (e.g. management, climate).
- Physical protection constrains the amount and rate of soil C accumulation.

Thanks

- For your attention
- Terrestrial Ecology Group at Argonne National Laboratory
- GCEP